Final Technical Report
on

HIGH-POWER MICROWAVE BREAKDOWN OF DIELECTRIC INTERFACES

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6. AUTHOR(S)
M. Kristiansen, L. Hatfield, and Mark Crawford

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Texas Tech University
Department of Electrical Engineering
P.O. Box 43102
Lubbock, Texas 79409-3102

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This is the final technical report for AFOSR Grant No. 91-0260, that began in May, 1991 and concluded two years later on May 15, 1993. The first objective of this project was to study the electrical breakdown, due to microwaves, which occurs on the surface of vacuum/atmosphere interfaces. This part of the contract was continuing work started on AFOSR Grant No. 88-102. The second objective of the project was to begin the development of a coaxial vircator.

Most of the breakdown results were reported in the previous annual technical report and will only be mentioned briefly. One particular window was tested during the last year of the contract and its results will be detailed in this report. Extensive simulations have been conducted on the coaxial vircator geometry with surprising results. All of the results from the coaxial vircator simulations are given in this report.

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Summary

This is an annual technical report for AFOSR Grant No. 91-0260, that began in May, 1991 and concluded two years later. The first objective of this project was to study the electrical breakdown, due to microwaves, which occurs on the surface of vacuum/atmosphere interfaces. This part of the contract was continuing the work started on AFOSR Grant No. 88-0102. The final report for that grant was submitted in November, 1991. The second objective of the project was to begin the development of a coaxial vircator.

The breakdown work was concluded by testing a new window geometry which both previous experimental work and simulation said should increase the breakdown strength, allowing more microwave power to propagate. The window was shaped with a 45° cone in the center of the window. The cone was convex on one side of the window and concave on the other side. The concave side was placed on the atmosphere side of the window. Simulations showed that the shape of the window provided a lensing effect which decreased the axial electric field on the atmosphere side of the window. Results of both simulations and experiments show that more power can be transmitted through this coned window than through a planar window.

The coaxial vircator is a configuration first published by Grigoryev, *et al*[1]. The geometry which we pursued reversed the diode polarity (grounded the cathode, pulsed the anode positive) in order to provide a more direct path for the energy from the pulsed power system to enter the diode. The geometry which we have modeled is similar to the reflex triode of Didenko, *et al*[2], in that is a rotated reflex triode geometry. For this reason we sometimes refer to it as a Coaxial Reflex Triode Vircator (CRTV.) From simulation, it appears that for a particular geometry, the coaxial vircator may have an extremely enhanced efficiency as compared to any other vircator or vircator-based microwave source. The results of these computer simulations are given in this report.

Project Overview

Window Breakdown Studies

The electrical breakdown of a dielectric window in the atmosphere due to a high-power microwave pulse has been investigated. Electrical breakdown of the window creates a plasma, through which the microwaves cannot propagate or are attenuated and/or refracted. If the breakdown strength can be improved, the microwave power through the window can be increased. Several factors have been studied, including the effects of different window materials, window shapes, window coatings, and ambient gases. Most of that work was completed under the previous contract. Under the present contract, devices at the end of the waveguide designed to mitigate the breakdown were studied.

The high-power microwaves are produced by a virtual cathode oscillator (vircator)[3]. An overall schematic drawing of the equipment is shown in Fig. 1. An electron beam is injected into a waveguide where the space-charge limit is exceeded, a virtual cathode that oscillates in space and time is formed, and the microwaves are extracted. The experiment consists of a 10 Ω, 12.5 ns one-way transit time, coaxial pulse forming line (PFL) that is charged from a Marx bank and switched into the vacuum diode through a self-breaking spark gap. The Marx tank, PFL, and output switch are all filled with transformer oil. The vacuum diode and the waveguide are evacuated with a diffusion pump and two mechanical roughing pumps. The best vacuum attained to date has been better than 1×10^{-6}. The end of the waveguide where the window is located is contained in an anechoic chamber which provides a reflection-free environment in which to observe the breakdown and measure the microwave power.

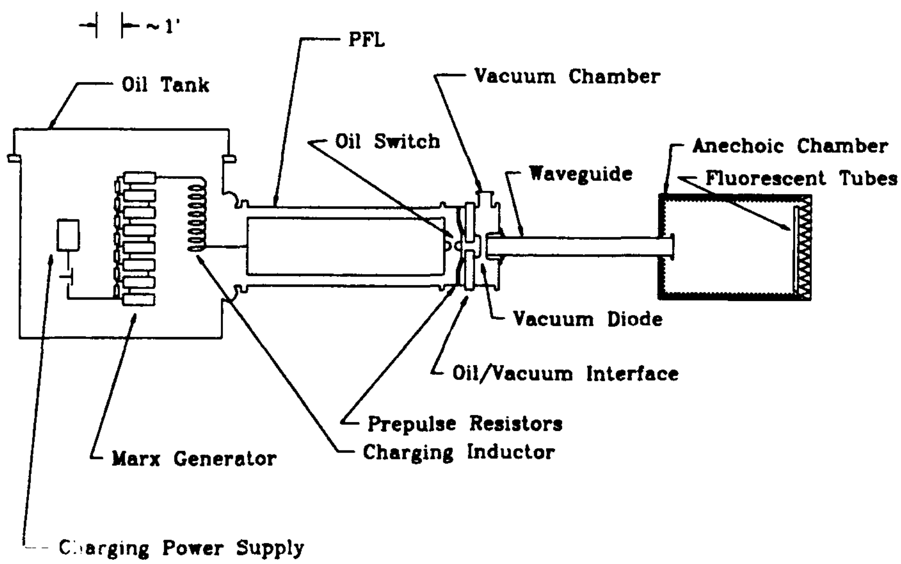


Figure 1. Schematic layout of the high-power microwave facility.

The diagnostic system is able to measure directly the Marx bank voltage, diode current, diode voltage, microwave power density at a given location in the radiation pattern, and the temporal variations in the light emitted from the breakdown. In addition, two mechanical cameras are placed to capture time-integrated photographs from inside the anechoic chamber. One camera views the window and captures the breakdown image, the other photographs the radiation pattern as detected by an array of fluorescent tubes placed at the end of the anechoic chamber.

In addition to the actual experimental equipment, a great deal of research has been done using the simulation code MAGIC[4]. MAGIC is a two-and-one-half dimensional, fully relativistic, particle-in-cell code. Using various university computing facilities, a number of simulations have been run to investigate the operation of the vircator and the effect of window geometry on field values.

Coaxial Vircator Development

A coaxial vircator is being designed to replace the planar vircator on the existing pulsed power system that is described above. MAGIC is being used to simulate the various geometries. The simulations provide a way to "test" each different geometry and study the operation of the diode. In effect, the simulations provide a way of prototyping each geometry, an invaluable tool for deciding on which is the proper configuration to construct. The coaxial geometry introduces several more variables into the design of a vircator. In addition to the anode-cathode (AK) gap distance and cathode radius, there is the anode radius, anode and cathode lengths, and the way the transition from the diode to the waveguide is made. A schematic representation of the version of the coaxial vircator which we are designing is shown in Fig. 2.

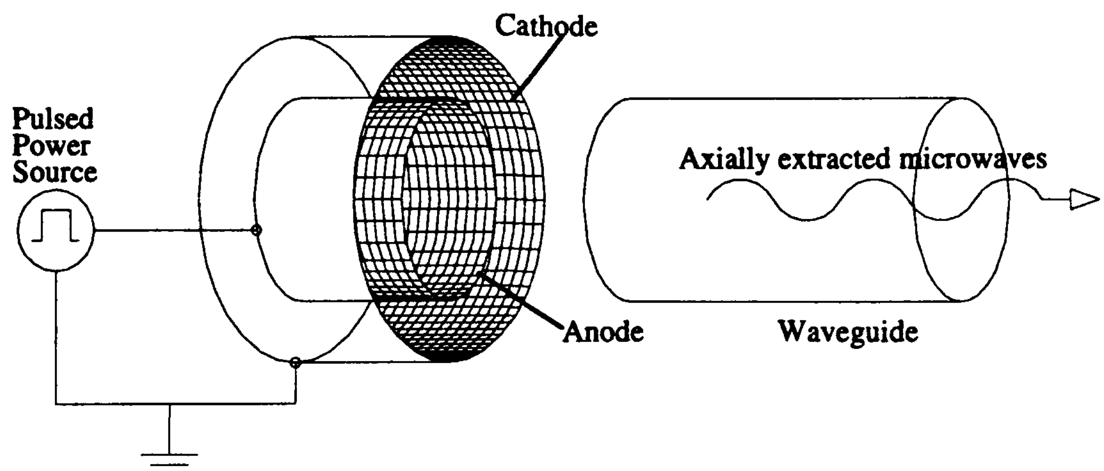


Figure 2. Sketch of the coaxial vircator microwave source.

The anode is a screen or foil or grid which is mostly transparent to electrons. The cathode is a cold emission surface like velvet. The anode is pulsed positive by the pulsed power source. Electrons are emitted from the cathode and are accelerated through the anode where they exceed the space charge limit and form an oscillating virtual cathode. The virtual cathode is more dense than in the planar geometry because of the radial geometry.

Research Results

<u>Window Breakdown Studies</u>

During the first year of this contract, a tuning stub was constructed in hopes that destructive interference from the wave reflecting off of the end of the waveguide would lower the axial electric field at the window surface. It is believed that for the microwave mode (TM_{01}) which is produced by the vircator, the axial electric field is responsible for the breakdown which occurs on the window. Also, during the first year of the contract, large permanent magnets were placed on the waveguide to deflect the electron beam and prevent it from hitting the window. The results of these actions were described in detail in the annual report for this project dated July, 1992, and will not be repeated here.

In the preceding year, two different window modifications were to be tested. The first was applying thin carbon films to the atmospheric side surfaces of the windows. It was hoped that the films could be applied here on the Texas Tech campus, but the system for applying these films was unavailable. It was decided that to determine properly the effects of such films would require more time than was available to the researchers during the contract period. Due to these circumstances, we have no results to report from this window treatment.

The second window modification to be tested was a window shape which we called a thin inverted cone. The thin inverted cone (TIC) geometry was developed from the previous result that an inverted 45° cone cut into a thick window provided reduced axial electric fields on the surface of the window in simulation and, when tested, had no breakdown in air. The thick window showed poor performance in transmitted power, however, due to the thickness of the lossy widow material. By keeping the inverted cone effect but reducing the window thickness, it was hoped that superior power transmission qualities could be achieved. A sketch of the window is shown in Fig. 3.

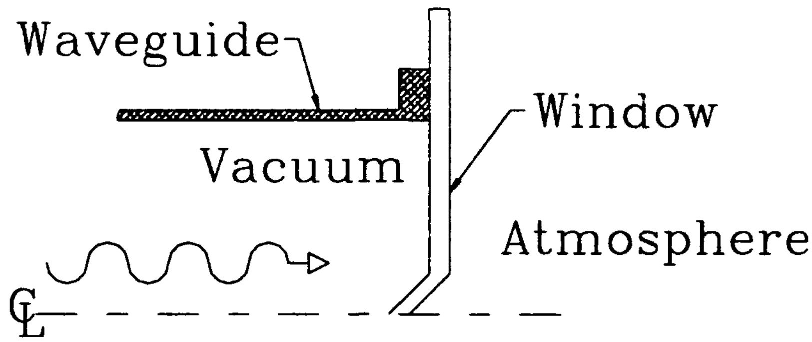


Figure 3. Schematic of thin inverted cone window.

Simulations were run to determine the effect of the shape of the window on the axial electric field of the microwaves as they propagate through the window. The simulations consist of a waveguide several wavelengths long terminating in the window which is in a large area simulating free space. An radial electric field is excited at the start of the waveguide which induces a TM_{01} mode at 2 GHz. These conditions accurately simulate the physical system. Figure 4 shows a contour plot of equal axial electric field lines. The dotted lines represent negative field values while the solid lines are positive. The first solid line next to a dashed line is the line of zero field. The field values for the lines immediately outside the window are marked in MV/m. The dotted region represents the dielectric window. The maximum axial electric field on the atmospheric surface of the window is around 1.55 MV/m

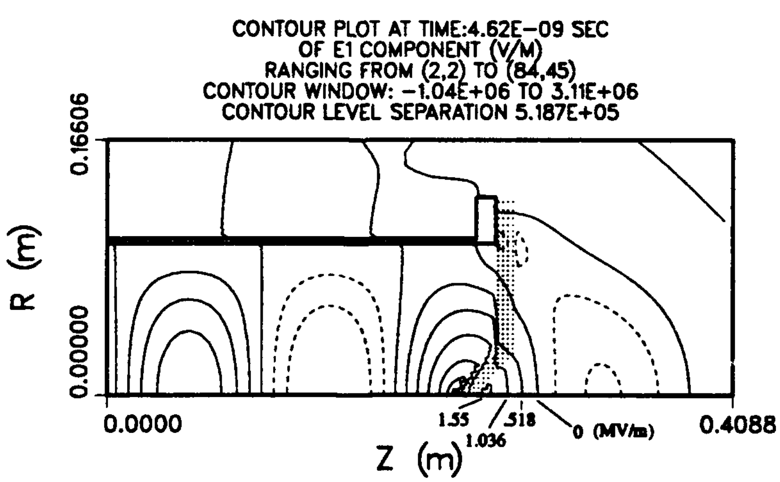


Figure 4. Equal field plot of E_z for the thin-inverted cone window.

The time of the plot in Fig. 4 was chosen because it represents the maximum axial electric field just outside the window. Field values are larger inside the vacuum, on the tip of the cone, but not on the atmospheric side of the window. For comparison purposes, the maximum axial electric field on the surface of a planar window in the same simulation is 2.14 MV/m. From this it is seen that the shape of the dielectric window provides a "lensing" effect which reduces the axial electric field on the atmospheric side of the window. This should allow more power to propagate through the window into free space.

Because the operational parameters of the vircator have changed dramatically since the times when most of the windows were tested under the last contract (see the final report for AFOSR Grant No. 88-0102, dated November 15, 1991 for details,) it is impossible to compare directly the performance of the TIC window to the other geometries which were tested. However, most of the recent shots have been taken on planar windows. The performance of the TIC in air can be compared to the performance of a planar window in air. The efficiency of propagated microwave energy to the energy in the electron beam provides a good quantitative value for comparison purposes. The following chart (Fig. 5) shows the beam energies, microwave energies and energy efficiencies for both the planar window and the TIC window. The values given are the average of five shots for each of the windows. The difference in the beam energies is probably the result of having to change the cathode velvet between the two series of shots. A different grade of cloth replaced the original due to the seasonal nature of white velvet (it is hard to find during the summer.)

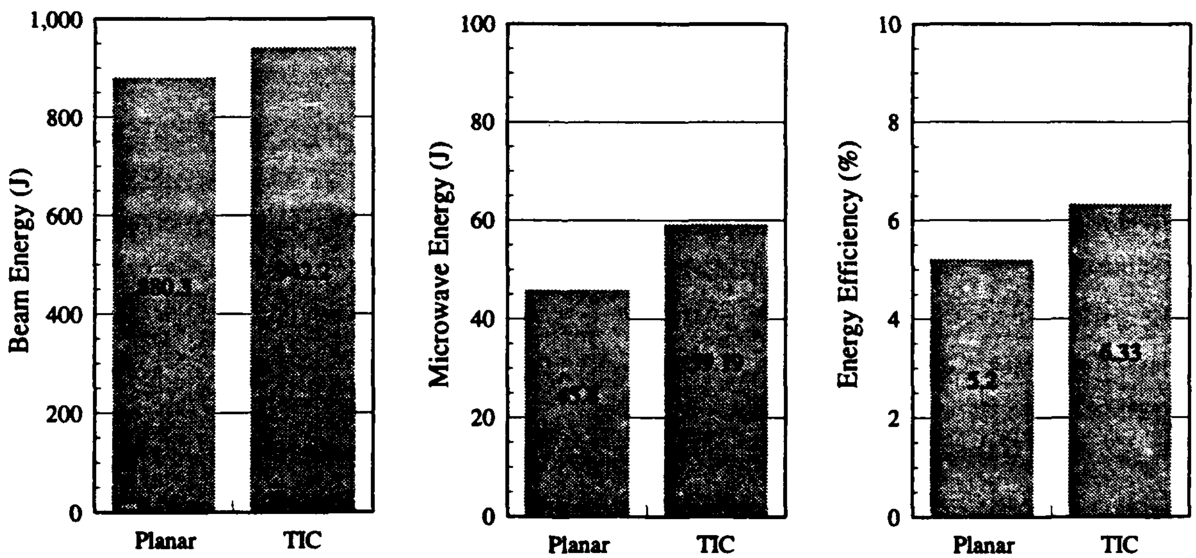


Figure 5. Comparison of the thin inverted cone (TIC) window with a planar window.

The efficiency of the thin-inverted-cone window at passing microwave energy is not the only factor in the number given in Fig. 5. That number is the overall efficiency of converting the beam energy to microwaves and propagating them into the atmosphere. While the efficiencies given above seem high, a simple planar vircator normally having an efficiency of around 1 to 2 %, the numbers are primarily used for a relative comparison. Due to errors in measuring, the efficiency of the system with the TIC window may not be as high as 6.33%, but it is higher than a planar window which has the same errors in measurement.

The breakdown which occurs on the TIC window seems to fill the entire concave cone, but is narrower away form the window than the breakdown which occurs on a planar window. Figure 6 shows two representative breakdown photographs, one on a planar window, the other on the thin-inverted-cone window. The left image is the breakdown occuring on a planar window, the left part of the breakdown is a reflection off the smooth window surface. The right image is the breakdown on the thin-inverted-cone window, there is no reflection because the surface has been machined.

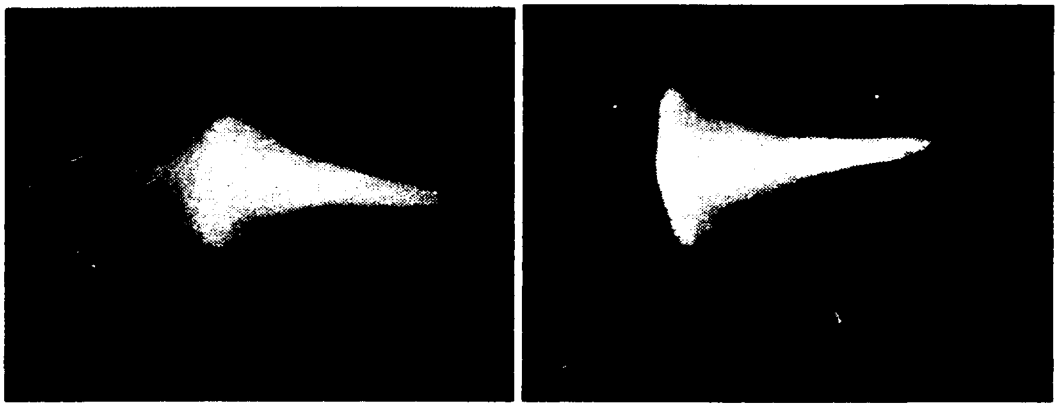


Figure 6. Photos of breakdown due to microwaves, left picture-planar window, right picture-thin-inverted-cone window.

With the testing of the thin-inverted-cone window, the studies on the window breakdown have been concluded. It has been shown over the last two contract periods that changing the window shape and surface roughness and window coatings can have an effect on the power which can be propagated through from the vacuum, where the microwaves are generated, to the atmosphere where they are propagated.

Coaxial Vircator Development

The vircator has several attributes which are appealing to the HPM community. Vircators do not require external magnetic fields with heavy coils and high-current power supplies. Also, the ability of vircators to be phase-locked to an external microwave source would allow large phased arrays of vircators to be constructed. The drawbacks of the vircator are the short output pulse length, relatively low frequency, and very low efficiency. A simple vircator will have an electron beam to microwave power efficiency of around 1%. Even the efficiency of highly developed vircators rarely exceeds around 10%. Thus, increasing the efficiency of the vircator is one of the major issues facing developers.

A vircator generates microwaves in two different (and competing) ways. First, a virtual cathode is formed when the diode current exceeds the space charge limit of the region just downstream from the anode. The virtual cathode oscillates in magnitude and position with the plasma frequency of the electron cloud. Microwaves are generated at this plasma frequency and propagate down the waveguide. The other microwave generation mechanism is the oscillation of electrons which reflex in the potential well between the real and virtual cathodes.

The two generation mechanisms produce different frequencies which compete for waveguide modes and reduce the efficiency of the device. Most attempts to increase the efficiency of the vircator focus on either matching the virtual cathode and reflexing electron frequencies or eliminating one of the generation mechanisms so that the other can dominate.

The idea for the cylindrical geometry was published by Grigoryev, *et al*[1]. A coaxial diode configuration has the aesthetically pleasing virtue that the virtual cathode formation will be fed from all directions by the radial electron beam. In Grigoryev's geometry, the anode is grounded and connected directly to the waveguide. While this is appealing for microwave coupling to the waveguide, it was felt that the TEM wave from the pulsed power system would have to take a convoluted route to reach the diode which could cause difficulty with stray inductance and slow risetime. It was decided that the grounded cathode design would be the geometry to pursue. The design work for this geometry has been done with simulations using MAGIC.

Since we were trying to design a source which would be constructed and installed on our existing equipment, a couple of the design parameters were fixed by the existing system. The waveguide radius is 98.4 mm and to ensure a single mode of propagation and to simplify the diagnostics, the frequency should be between 1.16 and 2.6 GHz (the TM_{01} and TM_{02} mode cutoff frequencies, respectively.) For comparison to the previous planar vircator on our system, the frequency should be as close to 2 GHz as possible.

Starting with these two criteria, simulations were run under two general schemes. The first placed the cathode radius equal to the waveguide radius (Fig. 7.)

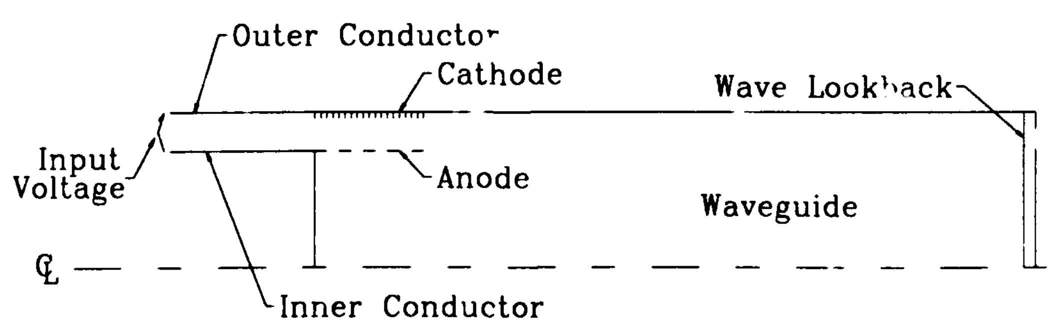


Figure 7. Sketch of CRTV geometry with cathode radius equal to waveguide radius.

The second geometry set the anode radius equal to the waveguide radius. This geometry adds an additional design parameter, the way in which the cathode radius transitions down to the waveguide radius (Fig. 8.)

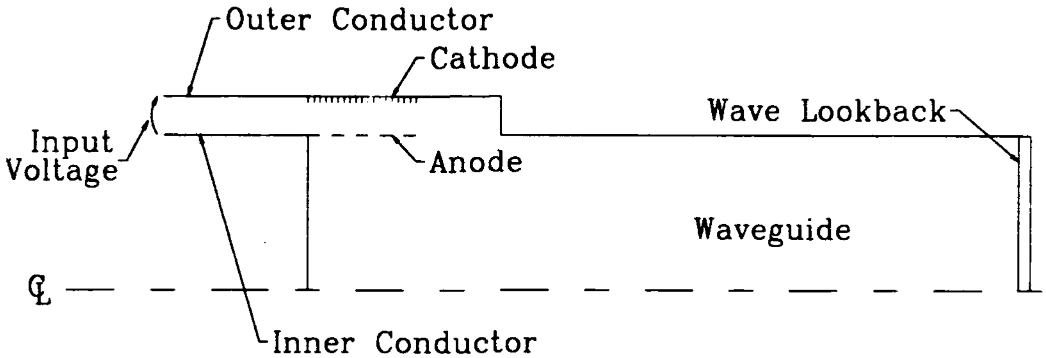


Figure 8. Sketch of CRTV geometry with anode radius equal to waveguide radius.

In each geometry, the AK gap length was set to 3.33 cm, the same as in our existing planar vircator. The cathode is simulated with a surface which emits particles at a rate dependent on the electric field. The anode is a thin foil which allows almost all particles to penetrate without scattering. A 900 kV, TEM wave with a hyperbolic tangent waveshape is launched into the coax from the left edge and propagates to the right.

The diode voltage is calculated by integrating the electric field along a line from the inner to the outer conductor. The diode current is determined by both a particle flux measurement at the surface of the cathode and by finding the azimuthal magnetic field in the coaxial region and calculating the enclosed current. Both types of "measurements" agree within a few percent on any particular geometry. Once the diode voltage and current have been determined, beam power and diode impedance can be calculated.

Microwave field "measurements" are made at the end of the waveguide. Each component (ρ,ϕ,z) of both the electric and magnetic field is calculated at three points along the waveguide radius. The frequency spectrum of each field measurement is plotted. By comparing field values of different frequency components, the power in each mode present can be determined. Comparing the power in the electron beam to the microwave power, an efficiency can be determined for each geometry.

The first geometry modeled was the cathode at the waveguide radius shown in Fig. 7. Phase-space plots of radial momentum versus radial position were encouraging. Representative phase-space plots of radial versus axial position and the corresponding radial momentum versus radial position are shown in Fig. 9.

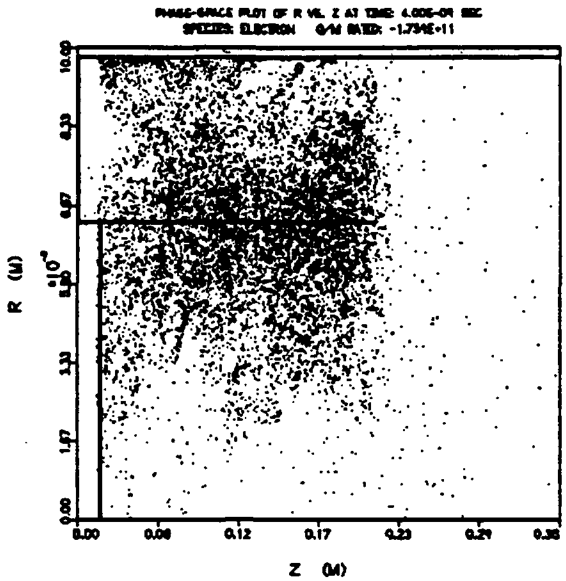


Figure 9a. Position plot of simulation with the cathode at the waveguide radius

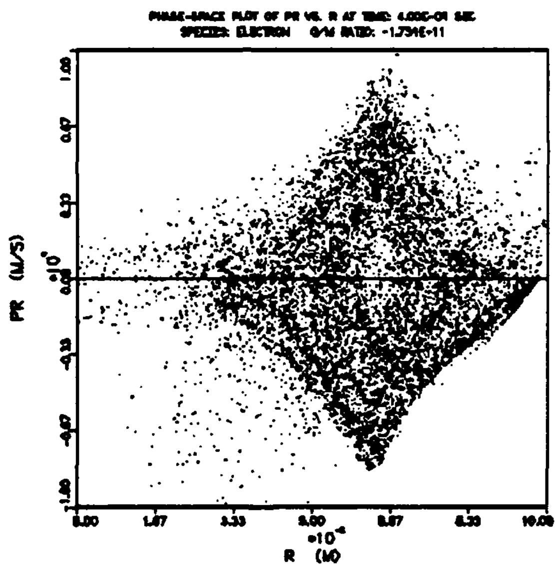


Figure 9b. Phase space plot for simulation with the cathode at the waveguide radius.

In Fig. 9a, the input TEM wave is launched from the left and electrons are emitted from the outer surface and accelerated inwards through the anode which sticks out from the end of the inner conductor. Figure 9b has the familiar diamond shape of a vircator phase-space plot. Electrons are being emitted from the right corner of the diamond and accelerating inwards towards the bottom corner where they pass through the anode. After passing through the anode, the particles decelerate and approach the left corner of the diamond, some tend to stay there, while many are repelled back toward the anode. Those which are reflected, accelerate outward until they reach the anode, and continue towards the cathode but are decelerated. These reflexing electrons continue in this cycle, tracing ever smaller diamonds as they lose energy to the radiated microwaves. By noting how well filled in the plot in Fig. 9b is, one would expect a great deal of microwave power from the reflexing electrons.

The following plot (Fig. 10) is the FFT of the radial electric field determined at a point midway between the center of the waveguide and the wall. The radial electric field is chosen because it is representative of the power which propagates in TM_{0n} modes.

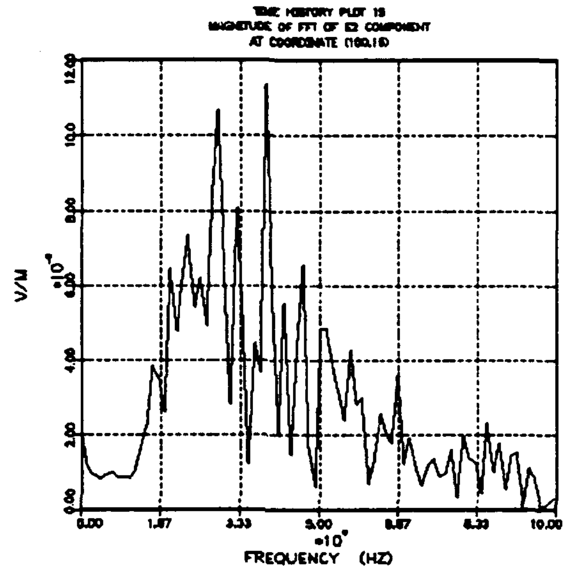


Figure 10. FFT of radial electric field measured midway between center and wall on simulation with the cathode at the waveguide radius (the horizontal axis is $\times 10^9$ Hz).

Note the wideband characteristics of the plot in Figure 10. Because of the requirements stated earlier, that a single frequency between 1.16 and 2.6 GHz is desirable, this geometry does not meet this requirement. It is believed that the wideband microwave generation is a product of the reflexing electrons. In all of the simulations in which the phase space plot was a filled in diamond, the spectrum of the generated microwaves was very wideband.

The second geometry placed the anode at the waveguide radius as shown in Fig. 8. A pair of phase-space plots for a this geometry is shown in Fig. 11.

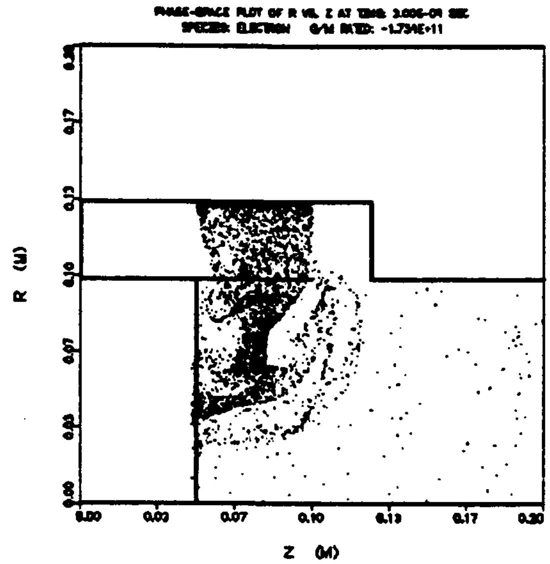


Figure 11a. Position plot of simulation with the anode at the waveguide radius

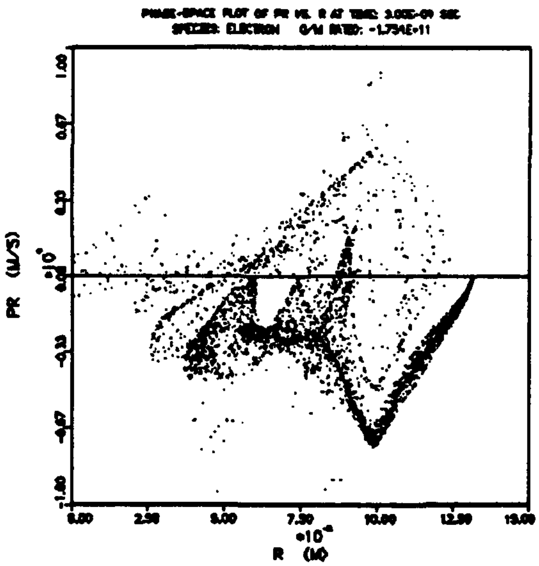


Figure 11b. Phase-space plots of simulation with the anode at the waveguide radius.

It can be seen that in Fig. 11a, a portion of the electrons in the inner anode region seem to be going around the end of the anode and returning to the AK gap. This is exactly what is happening. By placing (in the simulation) flux measurement surfaces on both the anode and in the region between the anode and the waveguide wall, it can be shown that substantially more particles take the around-the-end route than reflex back through the anode. Figure 11b shows that the familiar diamond shape is gone, most of the electrons accelerate through the anode but do not return through the anode. The action of the particles which cycle around the anode has been termed "electron recycling." The FFT of the radial electric field at the midpoint is shown in Fig. 12.

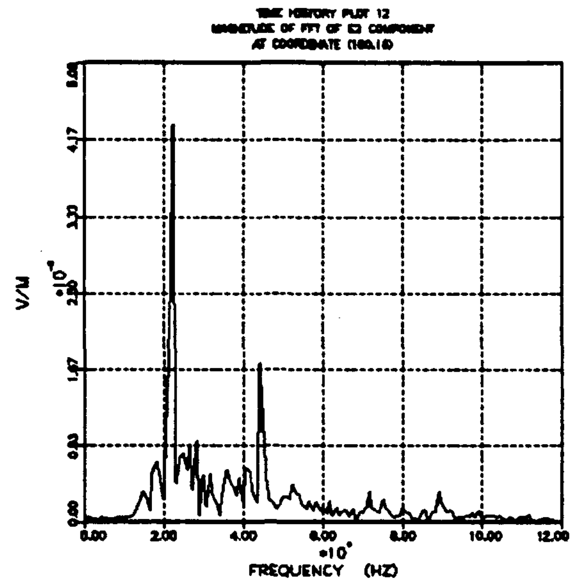


Figure 12. FFT of radial electric field at the midway point with the anode at the waveguide radius (the horizontal axis is $\times 10^9$ Hz).

When compared to the FFT in Fig. 10, it is obvious that there is a much more coherent radiation being produced by this geometry. The 2 GHz spike and the second harmonic are both clearly obvious. When this simulation was first run, it was thought that the recycling electrons were undesirable. The next simulation extended the anode screen, forcing the electrons to reflex through the anode. The results of that simulation showed a wideband microwave output with reduced field values in the desired frequencies. Reacting to that result, the next simulation was designed to enhance the recycling electron effect. The results showed increased recycling electrons and narrower frequency spectrum, with higher values in the desired field components. It appears that the recycling electrons have the effect of reducing the bandwidth and increasing the power in discrete frequencies.

In the subsequent simulations, several geometries were tried with the goal of increasing the recycling effect and output power. The best design to date has the transition region between the cathode and waveguide forming a forty-five degree angle. This particular geometry has been dubbed the "angle transition" geometry. Particle position and phase space plots are shown in Fig.'s 13a and 13b, respectively. When the microwave spectrum is calculated, Fig. 14, it shows even higher field values.

Power and efficiency calculations can be made for each of the simulations, as was stated earlier. Table 1 shows a sketch of the geometry, input voltage, beam power, microwave power, and efficiency. In certain cases, the microwave power could not be obtained because the mode could not be determined. Each of the calculations was made as close to 2 GHz as possible.

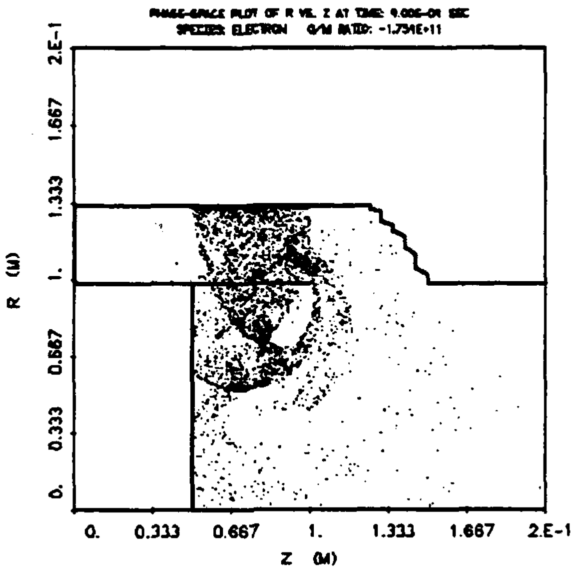


Figure 13a. Position plot of simulation with angle transition geometry.

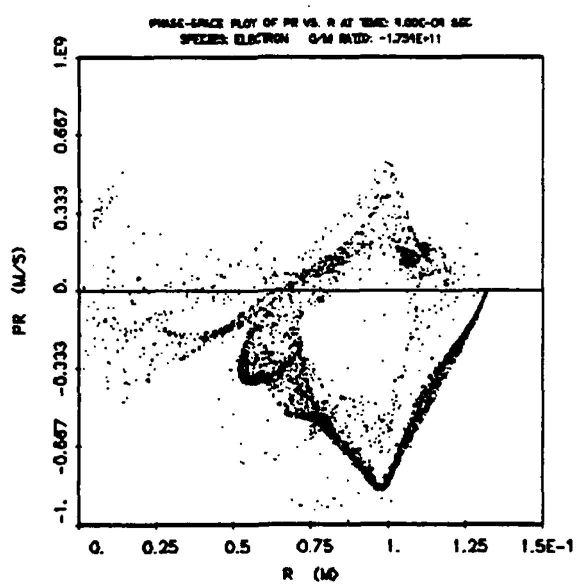


Figure 13b. Phase-space plots of simulation with angle transition geometry.

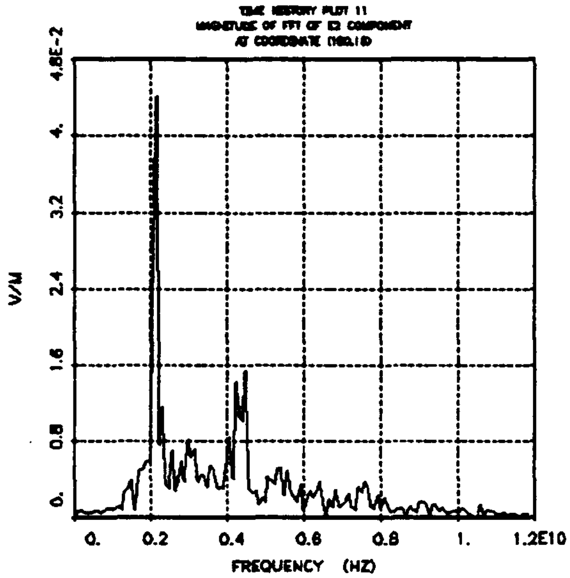
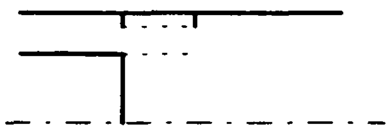
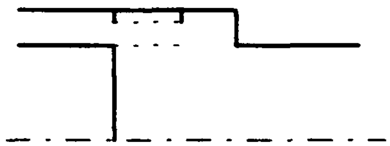
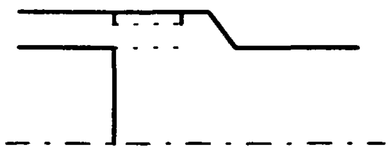
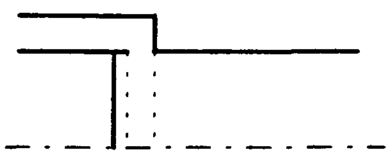


Figure 14. FFT of the radial electric field in the angle transition geometry (the horizontal axis is $\times 10^9$ Hz).

Table 1. Comparison of CRTV geometry simulations.

Sketch of Geometry	Input Voltage	Beam Power	Microwave Power	Efficiency
 cathode at waveguide	900 kV	55 GW	N/A	--
 anode at waveguide	900 kV	49.5 GW	33.6 GW	67.9%
 angle transition	900 kV	47.5 GW	34.6 GW	72.9%
 planar	900 kV	65.1 GW	47 MW	0.72%

For comparison purposes, a planar vircator geometry was simulated. The planar geometry paralleled the coaxial geometry as closely as possible. The same input transmission line, AK gap spacing and waveguide was used. In each case, the simulations were run under identical simulation parameters. The number and size of time steps were constant as well as the method of solutions.

The efficiency values for the two CRTV geometries seem inordinately high. The planar geometry was included to show that the method of efficiency calculation is reasonable. The planar geometry was not optimized for power output, but a simple vircator should have an efficiency on the order of 1-2%. That the planar simulation has an efficiency of almost 1% shows that the method of determining efficiency is probably not unreasonable. These results are recent and have not been extensively tested by other methods. Before claims of super-high-efficiency vircators can be made, additional simulation work and prototyping needs to be done.

It is believed that the recycling motion of the electrons replaces the reflexing of electrons. This alone should increase the efficiency of the microwave generation. It is, however, possible that the electrons get recycled in phase with the oscillations of the virtual cathode. Their cyclic motion generates an azimuthal magnetic field. The azimuthal magnetic field is a primary component of the TM_{On} which the virtual cathode naturally generates. The recycling adds to the generation of microwaves at the same frequency and in the same mode as the virtual cathode oscillation.

Continuing simulation and experimental work on the coaxial vircator is proceeding under a new AFOSR grant, No. F49620-93-1-0203. This is a one year grant which will end in May, 1994. The results of any future simulations and all experimental work will be reported in the technical report for that grant.

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1 V. P. Grigoryev, *et al*, "Experimental and Theoretical Investigations of Generation of Electromagnetic Emission in the Vircators," Proceedings of the 8th International Conference on High-Power Particle Beams, 1990, pp 1211-16

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Publications

During the contract period, two papers were written about several aspects of the research:

M. Crawford, S. Calico, M. Kristiansen, L. Hatfield, "Computer-Assisted Diagnostics on a High-Power Microwave System," to be published in the proceedings of the XXth International Conference on High-Power Particle Beams, Washington, D.C., June 1992.

M. Crawford, M. Kristiansen, L.L. Hatfield, "Cylindrically Symmetric Virtual Cathode Oscillator High-Power Microwave Source," to be published in the proceeding of the IXth Pulsed Power Conference, Albuquerque, NM, June 1993.

Personnel

Principal Investigators:	Dr. M. Kristiansen, C.B. Thorton/P.W. Horn Professor of Electrical Engineering and Physic Dr. L.L. Hatfield, Professor of Physics
Graduate Student:	Mark Crawford earned his M.S.E.E. in August, 1991 and is continuing his research on the experiment for his Ph.D. research.